Ten-year growth response of 70-year-old lodgepole pine to fertilization in Alberta

R.C. Yang

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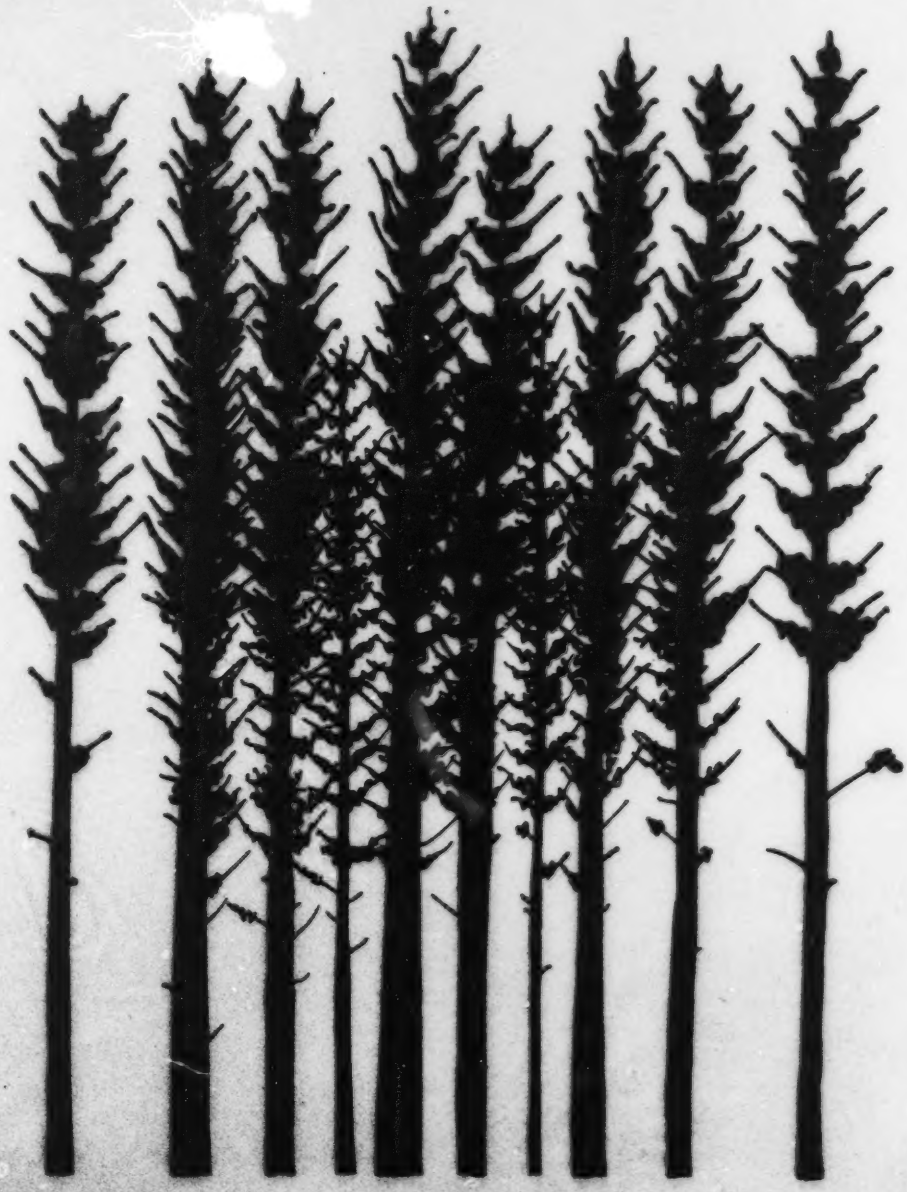

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TEN-YEAR GROWTH RESPONSE OF 70-YEAR-OLD LODGEPOLE PINE TO FERTILIZATION IN ALBERTA

R.C. Yang

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ABSTRACT

Fertilization of 70-year-old lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) stands in west-central Alberta with N, P, and S resulted after 10 years in increases in total and merchantable volumes of 34 and 33 m^3/ha on Coalspur soils and 31 and 28 m^3/ha on Mercoal soils. These represent increases of up to 50% in periodic volume increment. Addition of at least 188 kg/ha of N produced the most significant growth response on both soils. Addition of P at up to 94 kg/ha improved wood volume on Coalspur soils. The effect of S was inconclusive.

RESUME

La fertilisation de peuplements de pins tordus latifolié (*Pinus contorta* Dougl. var. *latifolia* Engelm.) de 70 ans, dans le centre-ouest de l'Alberta, au moyen de N, de P et de S, s'est traduite, 10 ans plus tard, par une augmentation respective des volumes totaux et marchands de 34 et de 33 m^3/ha à Coalspur et de 31 et de 28 m^3/ha à Mercoal. Il s'agit d'une augmentation pouvant atteindre 50% de l'augmentation périodique en volume. Dans les deux localités, l'ajout d'au moins 188 kg/ha de N a donné la croissance la plus notable. L'ajout de P à raison de 94 kg/ha a amélioré le volume à Coalspur. L'effet de S n'a pas été concluant.

CONTENTS

	Page
INTRODUCTION	1
METHODS	1
Study location	1
Description of the study areas	1
Experimental design and plot layout	3
Fertilizer application	3
Soil and foliar analysis	3
Measurement and analysis	4
RESULTS	6
Pretreatment stand conditions	6
Tree volume increment	7
Coalspur soils	7
Mercoal soils	10
Periodic stand increment	10
Tree mortality	10
Stand increment	10
DISCUSSION	13
CONCLUSIONS	15
ACKNOWLEDGMENTS	16
REFERENCES	16

FIGURES

1. Location of the study areas	2
2. Height-diameter curves of the Coalspur and Mercoal stands	5
3. Effects of N × P interactions on 10-year periodic volume increment of dominant-codominant trees on Coalspur soils	11
4. Effects of N × S interactions on 10-year periodic volume increment of dominant-codominant trees on Coalspur soils	11
5. Effects of N × S interactions on 10-year periodic volume increment of dominant-codominant trees on Mercoal soils	12

TABLES

1. Coded levels and rates of fertilizers used in the study	4
2. Stand characteristics prior to fertilization	7

Page

3. Physiochemical characteristics of Coalspur and Mercoal soils 8
4. Foliar N, P, and S concentrations in 70-year-old lodgepole pine stands before fertilization 9
5. Ten-year tree volume increment of dominant-codominant trees after N, P, and S fertilization 9
6. Significance of main and interactions effects on 10-year tree volume increment on Coalspur and Mercoal soils 10
7. Mortality rate of 70-year-old stands on the Coalspur and Mercoal sites based on 30 tagged trees ... 13
8. Ten-year stand increments after different N, P, and S treatments 14
9. Stand basal area, total volume, and merchantable volume increments for the 15 largest trees per plot on Mercoal soils 15

NOTE

The exclusion of certain manufactured products does not imply rejection nor does the mention of other products imply endorsement by the Canadian Forestry Service.

INTRODUCTION

Lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) is a predominant tree species in west-central Alberta and the interior of British Columbia. The yields from natural stands depend largely on stand density and site productivity (Smithers 1961; Johnstone 1976). Improving growth and yield of lodgepole pine through density control by thinning and spacing has been well documented (Alexander 1965; Dahms 1967; Bella and De Franceschi 1977, 1982; Johnstone 1981, 1982), but information on improving productivity through soil amelioration remains rather scanty. Cochran (1975, 1979) and Cochran et al. (1979) reported substantial responses to heavy N, P, and S fertilization in a thinned semimature stand in Oregon. Boyd et al. (1975) and Boyd and Strand (1975) investigated growth response of lodgepole pine to P, K, S, B, and N nutrients and reported that only N had a significant effect on basal area growth of 40-year-old pine stands in the British Columbia interior. N fertilizer alone improved the yield of a thinned lodgepole pine stand in western Alberta (Bella 1978).

As forest management passes into a more intensive phase, reliable information is needed on the effectiveness of these stand treatments for improving productivity under a variety of stand conditions. Fertilization, along with thinning and spacing, could become an important tool for managing lodgepole pine stands. It is imperative that the growth response to fertilization be well defined and that cost and benefit be calculated before the management option is used operationally.

This study was initiated with an objective to define the relationship between lodgepole pine tree and stand growth at different ages to various fertilization treatments on two important soils types that are most likely to benefit from fertilization. This report presents 10-year growth responses of two 70-year-old stands to various rates of N, P, and S fertilization. In conjunction with this experiment, a separate study (Baker 1973, 1977) was undertaken to monitor the transformations and movement of nitrogen fertilizer following its application in these stands. Baker's study provided insight into nutrient cycling in these stands so that the mensurational responses can be better understood.

METHODS

Study location

The study areas (Fig. 1) were located southeast of Hinton, Alberta (53°25'N, 117°34'W), on the lease area of St. Regis (Alberta) Ltd. Forests here are within the Lower Foothills Section (B.19a) of the Boreal Forest Region (Rowe 1972). Two fully-stocked 70-year-old lodgepole pine stands were selected on Coalspur (Orthic Gray Luvisol) and Mercoal (Podzolic Gray Luvisol) soils. The Coalspur stand was situated on the McLeod Cut-off Road (Legal Subdivision 5-14-50-23 and 1- & 8-15-50-23, W5), approximately 40 km southeast of Hinton. The Mercoal stand was south of Mercoal (Legal Subdivision 16-35-47-22 and 13-36-47-22, W5), approximately 90 km southeast of Hinton.

The area has a continental climate, characterized by long, cold winters and cool summers. The mean annual temperature is 1°C and the average frost-free period is 60-65 days. July is the warmest month, with a mean temperature of about 12°C. Approximately 50% of the annual precipitation of 51-56 cm comes as snow.

Description of the study areas

The soils of the Coalspur study area are predominantly Orthic Gray Luvisols with some Podzolic Gray Luvisol developed on Coalspur-Mercoal soil series under the Robb Association (Dumanski et al. 1972). These soils are developed on a till parent material of Cordilleran origin mixed with some colluvium. The area is situated approximately 1430 m above sea level (a.s.l.) and has a western to northern aspect with gently undulating to hilly topography. Soils on the upper and middle slopes are moderate to well drained, while soils on the lower slope are moist to wet.

The soils of the Mercoal study area are primarily Podzolic Gray Luvisols (Mercoal series) developed on clay loam-textured Cordilleran till with a light-gray silt loam-textured fluvioeolian veneer. The study area was situated approximately 1450 m a.s.l. and had a south-west to southeast aspect. An undulating to gently rolling topography resulted in moderately well to well-drained conditions.

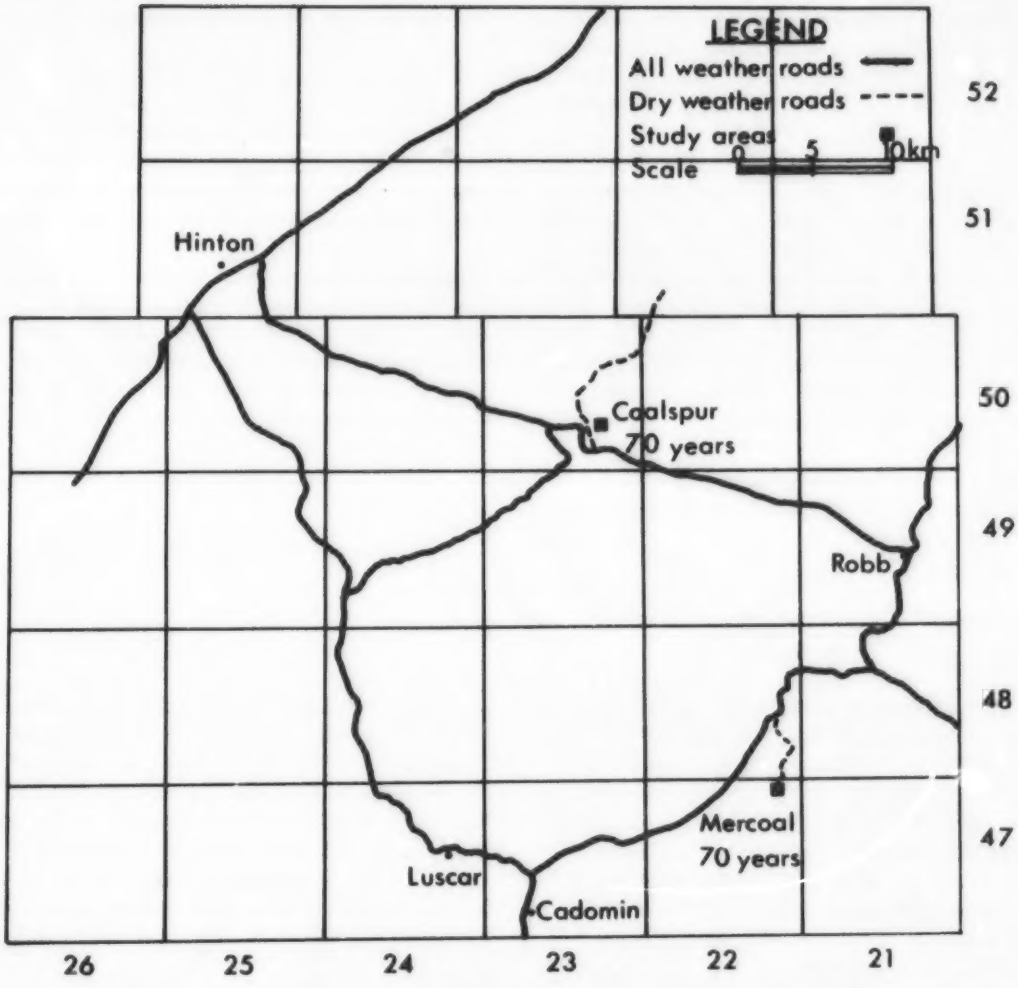

Figure 1. Location of the study areas.

The upperstory was chiefly lodgepole pine (over 90% by volume); alpine fir (*Abies lasiocarpa* (Hook.) Nutt.), black spruce (*Picea mariana* (Mill) B.S.P.), white spruce (*P. glauca* Mill.), poplar (*Populus* spp.), and willows (*Salix* spp.) occurred sporadically within the stand. White spruce advanced growth, mixed occasionally with lodgepole pine regeneration, occurred in clumps under broken canopy. Alder (*Alnus* spp.) was abundant on the upper positions of slopes in both areas. The ground cover consisted of feather moss species, or combinations of feather mosses and grasses. Commonly observed lesser vegetation included Labrador tea (*Ledum groenlandicum* Oeder), bearberry (*Arctostaphylos uva-ursi* Spreng), blueberry (*Vaccinium* spp.), bunchberry (*Cornus canadensis* L.), wild rose (*Rosa acicularis* Lindl.), and wild raspberry (*Rubus strigosus* Michx.). Vegetational association differed between these two sites; the Mercoal site was homogeneous and described as *Pinus contorta/Alnus crispa/Cornus canadensis*, whereas the Coalspur site was diversified and described as *Pinus contorta/Alnus crispa/Cornus canadensis*, *Pinus contorta-Picea mariana/Ledum groenlandicum/Pleurozium schreberi*, and *Pinus contorta/Viburnum edule/Aralia* (Corns 1978).

Experimental design and plot layout

A central composite rotatable second-order design (Cochran and Cox 1957) was selected to provide a general predictive relationship between tree and stand responses and fertilizer levels. Five nutrient levels (codes −1.68, −1, 0, 1, and 1.68) were tested, representing control, low, optimal, high, and supraoptimal nutrient levels. In theory, the optimal rate of a factor is determined by successive trials of the factor, and other levels are computed accordingly. The optimal rates of N, P, and S in this study were derived from other similar studies. Fourteen treatment combinations (Treatments 1-14, Table 1) and six identical treatments (Treatments 15-20) of the mid-level (Level 0) of each factor are required for three factors with five levels of fertilizer (Table 1). The experimental design was essentially a regression type; six repeating treatments at the 0 level were included to increase the prediction precision of the derived response surface equation at the presumably optimum level (0,0,0) of three fertilizers and to provide a measure of pure error. In addition to the above-mentioned 20 composite design treatments, four extra treatments (21-24) were also added to allow the analysis of results by two 2^3 factorials: Factorial 0 (Levels −1.68 and 0) and Factorial 1 (Levels −1 and 1) (Table 1).

Each study area was divided into three blocks containing 24 plots. The plot centers were established systematically on a square grid at approximately 30-m (1.5-chain) intervals. When a plot center fell within an abnormally open portion of the stand, the plot was omitted or moved to an adjacent fully-stocked portion of the stand. Circular plots (8.0-m radius) of one-fiftieth hectare (one-twentieth acre) were used. Each plot center was marked with an aluminum post bearing the plot number, and 10 thrifty trees closest to the plot center were tagged. Plot boundaries were marked with paint. A fertilizer treatment was randomly assigned to plots within the block.

Fertilizer application

The applied fertilizers and their composition are presented in Table 1. Nitrogen-free treatments were made using the required quantities of triple superphosphate and elemental sulfur, while phosphorus-free treatments were prepared by combining the required quantities of urea and sulfur. To minimize the contamination of the sulfur-free treatments by the phosphorus source, ammonium phosphate was used.

All fertilizer used in this study was provided by Sherritt Gordon Mines Ltd. The fertilizer combination for each plot was precisely weighed out, bagged, and identified by plot number in the laboratory. All of the fertilizer treatments were broadcast by using cyclone seeders in mid-May of 1972.

Soil and foliar analysis

A series of soil sampling points (17 in the Coalspur site and 22 in the Mercoal site) was established at each study area and a complete soil description was carried out. Samples were collected for nutrient analysis (N, P, K, Ca, Mg, and Na), pH, and percent organic carbon.

Soil pH was determined on a saturated soil paste using 1.0 mol/L KCl. A 1.0 mol/L (pH 7.0) solution of NH_4OAc (1:10 soil:solution ratio) (Chapman and Pratt 1961) was used to extract the exchangeable Ca, Mg, K, and Na. The ammonium acetate extractable cations were determined by atomic absorption spectroscopy (Perkin-Elmer Corporation 1968). Lanthanum was used to prevent interference from P and Al in the determination of Ca and Mg (David 1960). Organic carbon in the soils was determined by the Walkley-Black titrimetric wet oxidation method (Greweling and Peech 1965). Easily soluble P was first extracted with ammonium fluoride solution (Bray and Kurtz 1945) and determined with a Bausch and Lomb Spectronic 20 colorimeter. Total N in the soil was determined by the modified macro-Kjeldahl technique as outlined by Jackson (1958).

Table 1. Coded levels and rates of fertilizers[1] used in the study

Treatment	Factorial design	Nitrogen			Phosphorus			Sulfur		
		Coded level	Nutrient (kg/ha)	Fertilizer (kg/plot)	Coded level	Nutrient (kg/ha)	Fertilizer (kg/plot)	Coded level	Nutrient (kg/ha)	Fertilizer (kg/plot)
1	1	−1	76	2.58	−1	38	3.21	−1	23	0.46
2	1	1	300	12.45	−1	38	3.21	−1	23	0.46
3	1	−1	76	0.33	1	150	12.66	−1	23	0.46
4	1	1	300	10.19	1	150	12.66	−1	23	0.46
5	1	−1	76	2.58	−1	38	3.21	1	90	1.82
6	1	1	300	12.45	−1	38	3.21	1	90	1.82
7	1	−1	76	0.33	1	150	12.66	1	90	1.82
8	1	1	300	10.19	1	150	12.66	1	90	1.82
9[2]	0	−1.68	0	0	0	94	9.69	0	56	1.05
10	—	1.68	377	14.67	0	94	7.94	0	56	1.14
11	0	0	188	8.28	−1.68	0	0	0	56	1.14
12	—	0	188	4.49	1.68	188	15.88	0	56	1.14
13	0	0	188	6.39	0	94	7.94	−1.68	0	0
14	—	0	188	6.39	0	94	7.94	1.68	113	2.29
15	0	0	188	6.39	0	94	7.94	0	56	1.14
16	0	0	188	6.39	0	94	7.94	0	56	1.14
17	0	0	188	6.39	0	94	7.94	0	56	1.14
18	0	0	188	6.39	0	94	7.94	0	56	1.14
19	0	0	188	6.39	0	94	7.94	0	56	1.14
20	0	0	188	6.39	0	94	7.94	0	56	1.14
21	0	0	188	8.28	−1.68	0	0	−1.68	0	0
22[2]	0	−1.68	0	0	0	94	9.69	−1.68	0	0
23	0	−1.68	0	0	−1.68	0	0	0	56	1.14
24	0	−1.68	0	0	−1.68	0	0	−1.68	0	0

[1] Nutrient sources: Nitrogen—urea (46-0-0) and ammonium phosphate (11-55-0).
Phosphorus—ammonium phosphate (11-55-0).
Sulfur—elemental sulfur (100% S).

[2] Triple superphosphate (0-45-0) used.

Foliar samples of the current year's growth on the uppermost lateral branches of three dominant trees per plot were gathered in the fall of 1971 prior to fertilization and in the falls of 1972 and 1973 following fertilization. Total nitrogen, phosphorus, and sulfur foliage contents were determined using the procedures outlined by Kalra (1971). Changes in foliar nutrient contents following treatment and relationship between nutrient contents and growth response will be analyzed and reported separately.

Measurement and analysis

The diameters at breast height outside bark (dbhob) of all living trees in each plot were first tallied in the fall of 1971. A sufficient number of heights was also measured to construct a reliable height-diameter curve (Fig. 2) for each area. After 10 growing seasons, the plots were remeasured in the summer of 1981; dbhob of all living trees in each plot was tallied by species.

Some studies have reported that tree response to fertilization is largely found in the upper portion of the stem (Woollons and Will 1975). To determine accurately tree volume increment after fertilization, three dominant or codominant trees in each plot were felled for stem analysis. Disks at 0.3 m stump, breast height (1.37 m), 3.05 m, 6.1 m, base of live crown, and other height positions of major changes in bole shape were obtained.

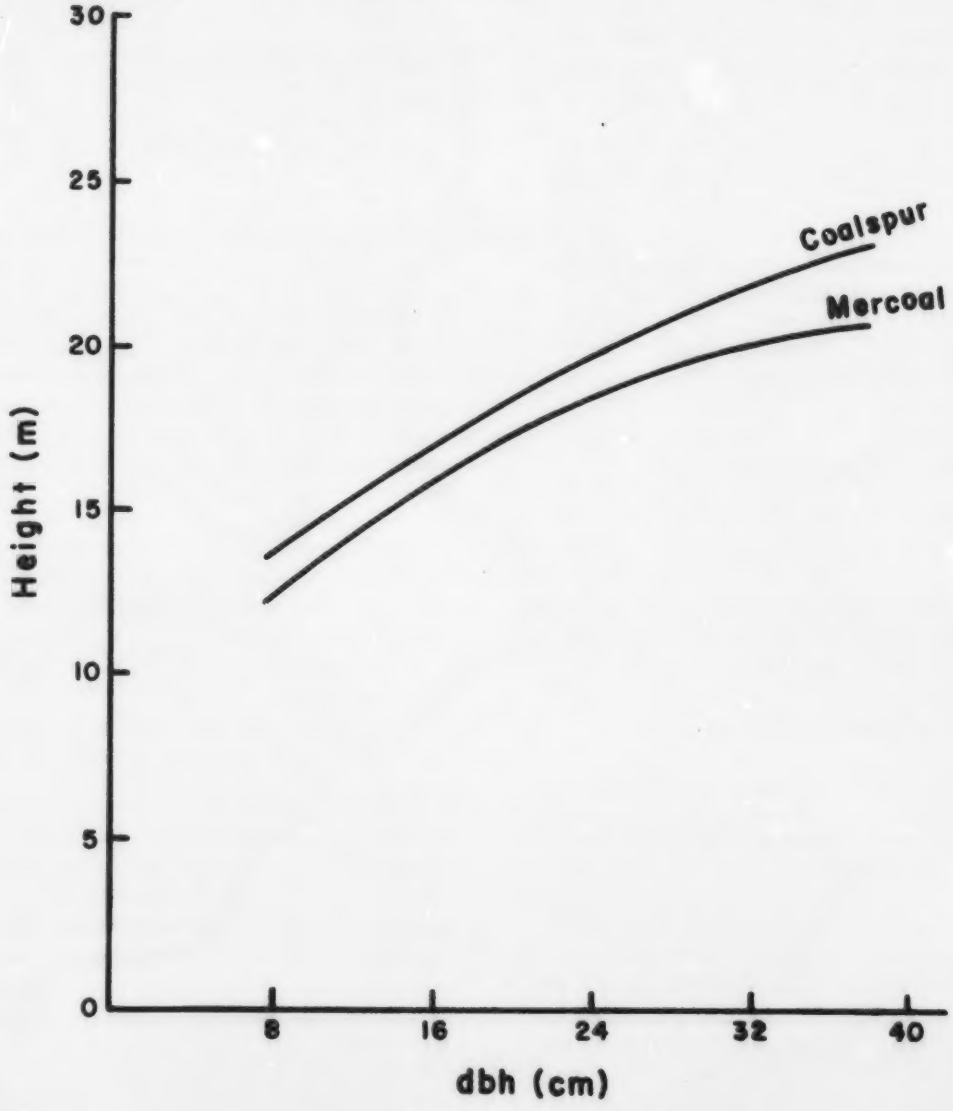

Figure 2. Height-diameter curves of the Coalspur and Mercoal stands.

Ten-year tree periodic volume increment (PVI) was determined from stem analysis. Tree volumes prior to fertilization and 10 years after fertilization were determined for each sample tree by the Smalian formula. PVI was obtained by difference.

Total and merchantable volume increments were obtained from two successive tree dbhob tallies in conjunction with the derived height-diameter equation for each area (Fig. 2). Total and merchantable volumes were computed for plot trees individually and summed up for stand volumes. Ten-year periodic stand total and merchantable volume increments were estimated by difference.

Total volume of plot trees was obtained by using the following volume equations (Johnstone 1976):

1. Trees < 8.9 cm (3.5 in.) dbhob
   $V = 0.0232 + 0.00253D^2HT$

2. Trees 9.1-21.6 cm (3.6-8.5 in.) dbhob
   $V = -0.0949 + 0.00272D^2HT$

3. Trees > 21.8 cm (8.6 in.) dbhob
   $V = 2.4328 + 0.00227D^2HT$

where V, D, and HT denote volume (cu. ft.), dbhob (in.), and tree height (ft.), respectively. Tree height was estimated from the following regressions:

$$HTc = 32.27 + 4.2969D - 0.0916D^2$$

$$HTm = 25.73 + 5.1921D - 0.1584D^2$$

where HTc and HTm are total height (ft.) for trees in the Coalspur and Mercoal sites.

Merchantable volumes, based on a 10.16-cm (4.0-in.) diameter inside bark (dib) top and a 0.30-m (1.0-ft.) stump, were calculated for all trees >11.68 cm (4.6 in.) dbhob using Honer's (1967) conversion functions for lodgepole pine. These are as follows:

$$X = (4.0/D)^2 \times (1.0 + 1.0/HT)$$

$$VM = V \times (0.9658 - 0.1278X - 0.8108X^2)$$

where X is as defined above, VM is the merchantable volume (cu. ft.), and D, HT, and V are as defined above. All measurements and computations were initially performed in imperial units and subsequently converted into SI units.

The design called for analysis by the response surface method; however, the response equations so derived were inadequate in approximating the true response surface. In all cases, the equations explained only 30-40% of the variation in the response variables, and the lack of fit terms, a measure for model fitting, was highly significant. The inadequacy of the composite design to characterize growth response in forest fertilization trials has been discussed in detail by Yang (1983).

Forest managers are primarily interested in the amount of wood gains resulting from various fertilizer treatments. Thus, periodic volume increment data were first analyzed by the randomized complete block design to determine the effects of fertilizer combinations on tree and stand growth. The analysis provided a test for difference in means between a fertilizer combination and the unfertilized control. To explore response trends to increases in N, P, and S and possible interacting effects among added nutrients on tree and stand increments, the two nested factorial measurements were analyzed. Initial volume and basal area were used as the covariates to adjust periodic diameter, tree volume, and stand increments in all analyses. These increments were highly correlated with ther initial values.

RESULTS

Pretreatment stand conditions

Table 2 summarizes statistics of the two sampled stands. The productivity of the Mercoal stand was slightly higher than that of the Coalspur stand, as indicated by larger dbh, total volume, and basal area per hectare.

Soil characteristics (Table 3) suggest that soil fertility in both areas was similar; however, total nitrogen and percent organic carbon on the Mercoal soils were somewhat higher than those on the Coalspur for all soil horizons. Total phosphorus, on the other hand, was higher on the Coalspur soils. Both soils were acidic, the Mercoal soils more so than Coalspur.

Table 2. Stand characteristics prior to fertilization

Treatment	Coalspur			Mercoal		
	Diameter (cm)	Basal area (m^2/ha)	Total volume (m^3/ha)	Diameter (cm)	Basal area (m^2/ha)	Total volume (m^3/ha)
1	16.06	33.55	287.77	17.60	28.83	240.76
2	17.23	28.80	250.11	17.45	35.19	291.90
3	14.92	33.76	279.61	15.98	37.06	297.98
4	17.27	31.88	280.74	15.44	38.89	306.18
5	18.44	27.78	245.71	16.99	36.63	300.45
6	16.43	29.31	250.34	18.08	31.92	271.90
7	15.39	24.00	202.16	17.49	34.27	286.51
8	16.97	27.55	242.51	17.08	36.98	305.51
9	17.83	32.57	284.31	16.88	33.51	273.42
10	15.41	33.56	281.17	17.86	29.89	249.98
11	15.02	32.38	267.31	18.61	31.81	273.14
12	16.59	32.18	276.14	16.02	37.55	299.78
13	15.72	30.82	259.03	18.00	27.69	232.30
14	15.26	31.44	259.83	16.73	33.72	274.97
15-20	16.39	31.93	273.81	18.31	32.65	275.62
21	16.41	36.23	312.92	17.70	35.63	297.59
22	15.80	29.67	251.40	18.54	33.06	279.40
23	17.45	33.11	292.02	19.36	27.49	237.29
24	16.06	29.17	246.78	17.23	37.10	304.07
Average	16.35	31.22	267.16	17.62	33.46	278.20

Analysis of nutrient status in foliage before fertilization indicated that total N and total P in the needles of the 70-year-old lodgepole pine trees were practically identical in both areas. Sulfur content was slightly higher on the Coalspur soils than on the Mercoal, but the difference was not significant at the 5% level (Table 4).

Nutrient requirements and foliar nutrient contents of growing trees or stands is believed to change with age (Miller et al. 1981). Data from this area, however, showed no correlations between stand age and foliar N and P contents of lodgepole pine. The foliar nutrient contents judged by Swan's (1972) standard indicated moderate deficiency in N and deficiency to sufficiency in P (Table 4). These stands were therefore expected to respond more strongly to N than to P.

Sulfur content averaged 406 and 373 $\mu g/g$ for the Coalspur and Mercoal stands, respectively. These foliar S contents are low compared with those reported by Beaton et al. (1965) for lodgepole pine in British Columbia. Sulfur content in biological materials is difficult to determine (Turner 1979).

Tree volume increment

Ten-year periodic volume increment (PVI) values of dominant and codominant trees are presented in Table 5, and significance levels of the main and interaction effects are shown in Table 6 for the two nested factorials.

It is noticeable in Table 6 that the block effect is highly significant on Coalspur but insignificant on Mercoal soils. Because the effect indicates the homogeneity of site productivity within the experimental area, the results are in good agreement with the vegetation classifications described in the Study Area section.

Coalspur soils

Eight of the 18 fertilizer treatments significantly improved tree PVI on Coalspur soils (Table 5). All but one of these treatments received N at dosages of 188 kg/ha or higher, suggesting that N was the most beneficial nutrient for lodgepole pine on these soils. This conclusion was further substantiated by the analysis of

Table 3. Physiochemical characteristics of Coalspur and Mercoal soils

Horizon		Thickness (cm)	pH	Exchangeable cations (μg/g) Na	K	Ca	Mg	% organic matter	Total P (μg/g)	Total N (μg/g)
Coalspur										
LFH	Avg	5.3	4.7	25	1 439	6 634	1 003	48.5	360	12 155
	Max	8.0	5.6	41	2 655	13 202	2 015	71.0	772	18 248
	Min	3.0	3.8	15	825	2 156	581	30.5	94	9 261
Ae_1	Avg	10.5	4.7	14	207	2 194	269	1.6	26	955
	Max	22.0	5.2	25	454	4 992	467	4.1	57	2 264
	Min	5.0	4.4	9	94	1 398	139	0.8	4	532
Ae_2	Avg	9.2	4.9	9	289	2 198	275	—	23	978
	Max	—	—	—	—	—	—	—	—	—
	Min	—	—	—	—	—	—	—	—	—
Ab	Avg	10.2	—	—	—	—	—	—	—	—
	Max	20.0	—	—	—	—	—	—	—	—
	Min	3.0	—	—	—	—	—	—	—	—
Bt	Avg	20.4	5.0	16	86	2 650	413	0.4	9	321
	Max	30.0	5.4	32	125	3 682	543	0.5	16	412
	Min	14.0	4.8	7	47	1 522	255	0.3	4	274
Bc	Avg	9.3	—	—	—	—	—	—	—	—
	Max	18.0	—	—	—	—	—	—	—	—
	Min	6.0	—	—	—	—	—	—	—	—
C	Avg	—	5.5	21	86	3 716	460	0.5	8	303
	Max	—	7.0	28	113	12 514	793	0.6	21	446
	Min	—	4.9	14	63	2 488	361	0.4	2	34
Mercoal										
LFH	Avg	6.1	3.9	51	1 568	3 096	658	51.4	291	13 433
	Max	9.0	4.8	304	2 381	4 300	951	57.5	610	14 835
	Min	5.0	3.4	16	684	1 800	353	41.7	132	9 789
Ae_1	Avg	7.9	3.4	18	109	978	101	2.0	21	1 223
	Max	50.0	3.8	23	160	5 700	208	2.8	42	1 552
	Min	4.0	3.1	14	74	300	54	1.3	8	691
Bf	Avg	5.1	4.0	18	102	1 610	220	1.5	7	995
	Max	9.0	4.8	44	164	8 900	426	2.3	43	1 432
	Min	2.0	3.7	7	59	300	56	0.6	0	44
Ae_2	Avg	7.3	—	—	—	—	—	—	—	—
	Max	13.0	—	—	—	—	—	—	—	—
	Min	4.0	—	—	—	—	—	—	—	—
Bt	Avg	16.5	4.1	18	90	2 736	535	0.5	6	490
	Max	27.0	5.0	23	160	5 600	733	0.7	18	669
	Min	9.0	3.9	9	47	900	235	0.3	1	283
Bc	Avg	11:6	—	—	—	—	—	—	—	—
	Max	25.0	—	—	—	—	—	—	—	—
	Min	4.0	—	—	—	—	—	—	—	—
C	Avg	—	4.3	18	106	3 978	722	0.4	17	434
	Max	—	5.1	23	164	5 874	794	0.5	25	592
	Min	—	4.1	14	57	2 850	630	0.2	2	312

Table 4. Foliar N, P, and S concentrations in 70-year-old lodgepole pine stands before fertilization

	Coalspur		Mercoal	
	Mean	S.D.[a]	Mean	S.D.
N (%)	1.10	0.166	1.10	0.064
P (%)	0.11	0.0085	0.11	0.0075
S (μg/g)	406	60.7	373	86.6

[a] S.D. = standard deviation.

Table 5. Ten-year tree volume increment (dm^3) of dominant-codominant trees after N, P, and S fertilization

	Coalspur			Mercoal		
Treatment	Initial volume	10-yr increment	Adjusted increment	Initial volume	10-yr increment	Adjusted increment
1	350.3	111.3	110.1	337.9	121.3	126.5***
2	406.3	155.2	139.8***	357.4	120.5	120.9***
3	305.9	95.7	105.8	336.9	107.4	112.8**
4	393.0	121.5	109.5	286.6	98.3	115.9***
5	384.4	117.3	107.5	357.8	90.5	90.8
6	370.4	167.0	160.7***	403.4	122.7	111.9***
7	317.6	127.1	133.4**	337.7	88.5	93.7
8	384.1	132.5	122.7**	365.8	123.7	122.1***
9	388.1	102.1	91.3	314.3	80.0	91.6
10	304.0	128.8	139.4***	354.2	134.1	135.3***
11	333.0	80.1	83.3	401.0	105.3	95.2
12	352.6	115.1	113.4	314.5	99.0	109.9**
13	306.0	125.7	138.8***	344.7	120.7	124.2***
14	289.1	103.0	117.4	278.3	96.8	116.4***
15-16	341.4	123.5	124.6**	386.8	120.0	113.3**
21	335.6	125.5	128.1**	377.4	111.7	107.3
22	318.2	84.9	91.9	384.7	88.3	82.1
23	369.4	88.0	83.5	409.0	121.0	109.0
24	346.1	95.6	95.5	336.6	63.6	69.1

** Treatment means differ from the control at the 1% level.
*** Treatment means differ from the control at the 0.1% level.

variance for the two 2^3 factorials (Table 6). Further, P, S, and interactions N × P, N × S, and P × S also significantly affected PVI.

Table 6. Significance of main and interactions effects on 10-year tree volume increment on Coalspur and Mercoal soils

Source of variation	Coalspur		Mercoal	
	Factorial 0	Factorial 1	Factorial 0	Factorial 1
Block	***	***	ns	ns
N	***	**	***	ns
P	*	**	ns	ns
S	**	**	ns	*
N × P	ns	***	ns	ns
N × S	*	ns	**	ns
P × S	*	ns	ns	ns
N×P×S	ns	ns	ns	ns2

* Significant at the 5% level.
** Significant at the 1% level.
*** Significant at the 0.1% level.
ns = not significant

Figures 3 and 4 illustrate the effects of N × P and N × S interactions on the PVI. At 188 kg/ha of N, an increase of P from 0 to 94 kg/ha enhanced PVI from 104 to 127 dm^3. At 300 kg/ha of N, however, tree PVI was reduced as P increased from 38 to 150 kg/ha (Fig. 3). This suggested that application of P in the range of 38-94 kg/ha would be sufficient for lodgepole pine on these soils.

The effects of S on PVI of dominant and codominant trees on Coalspur soils are somewhat inconsistent. At 188 kg/ha of N, an increase of S from 0 to 56 kg/ha decreased PVI, while S enhanced tree PVI as it increased from 23 to 90 kg/ha at both 76 and 300 kg/ha of N (Fig. 4).

Mercoal soils

Eleven of 18 treatments on the Mercoal soils showed significant response in PVI (Table 5). The percent responses of fertilized trees were substantial but the absolute value of PVI on the Mercoal soils was smaller than on the Coalspur soils (Table 5).

Factorial analyses confirmed again that N was the most beneficial nutrient; however, an increase of N from 76 to 300 kg/ha (Factorial 1) did not significantly improve tree PVI on the soils (Table 6). In addition, N × S and S effects were significant at Factorial 0 and 1 levels, respectively (Table 6). In contrast to that, on the Coalspur soils application of 56 kg/ha (Level 0) of S alone increased tree PVI from 80 to 140 dm^3. The addition of 56 kg/ha S, however, seemingly depressed PVI as 188 kg/ha of N was added (Fig. 5).

Periodic stand increment

In the foregoing, fertilization responses were evaluated from the periodic increments of surviving dominant and codominant trees. This approach may be biologically appropriate, but to forest managers the overriding criteria are net gain in total or merchantable volume and value of the fertilized stands. The periodic net stand increment is gross increment minus tree mortality during the period. Excessive mortality can negate any positive effect of fertilization.

Tree mortality

In the absence of external damage (from wind or animal and pest infestation), tree mortality results from competition for growing space, water, and nutrients. Added nutrients enhance the competitive advantage of dominant and codominant trees, and consequently a higher mortality rate among suppressed trees in fully-stocked stands is anticipated after fertilization.

Data on mortality are incomplete, as only 10 vigorous trees surrounding the plot center on each plot were tagged. Table 7 shows the percent mortality based on 30 tagged trees for each treatment by soil type. The mortality rate was appreciably higher on the Mercoal soils than on the Coalspur in the 10-year period, which is not surprising because the Mercoal soils supported more stems per hectare than the Coalspur. These results support the theory that fertilization accelerates the natural thinning process. Conversely, fertilizing stands with space for crown and root expansion might be more cost-effective.

Stand increment

Table 8 summarizes 10-year periodic increments in basal area, total volume, and merchantable volume per hectare for the two lodgepole pine stands. The Coalspur stand showed greater response than the Mercoal to the fertilization. Four out of the 18 fertilizer treatments

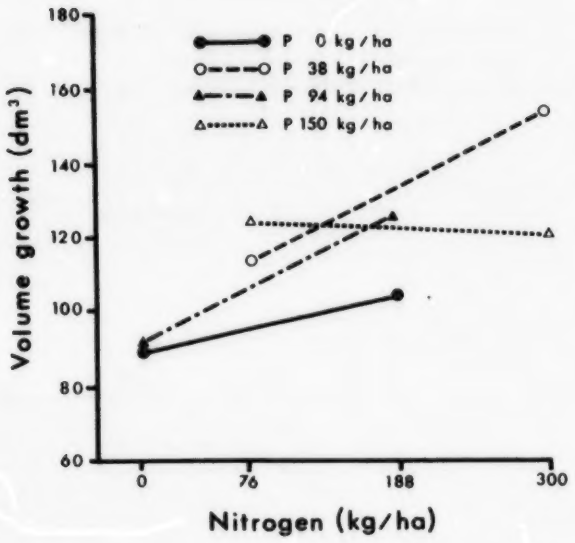

Figure 3. Effects of N × P interactions on 10-year periodic volume increment of dominant-codominant trees on Coalspur soils.

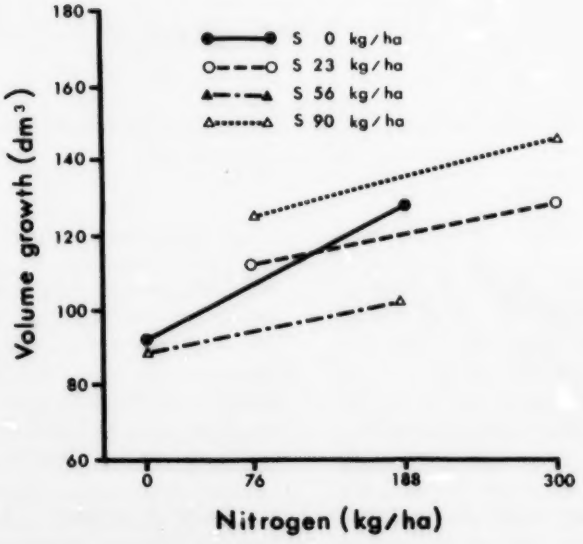

Figure 4. Effects of N × S interactions on 10-year periodic volume increment of dominant-codominant trees on Coalspur soils.

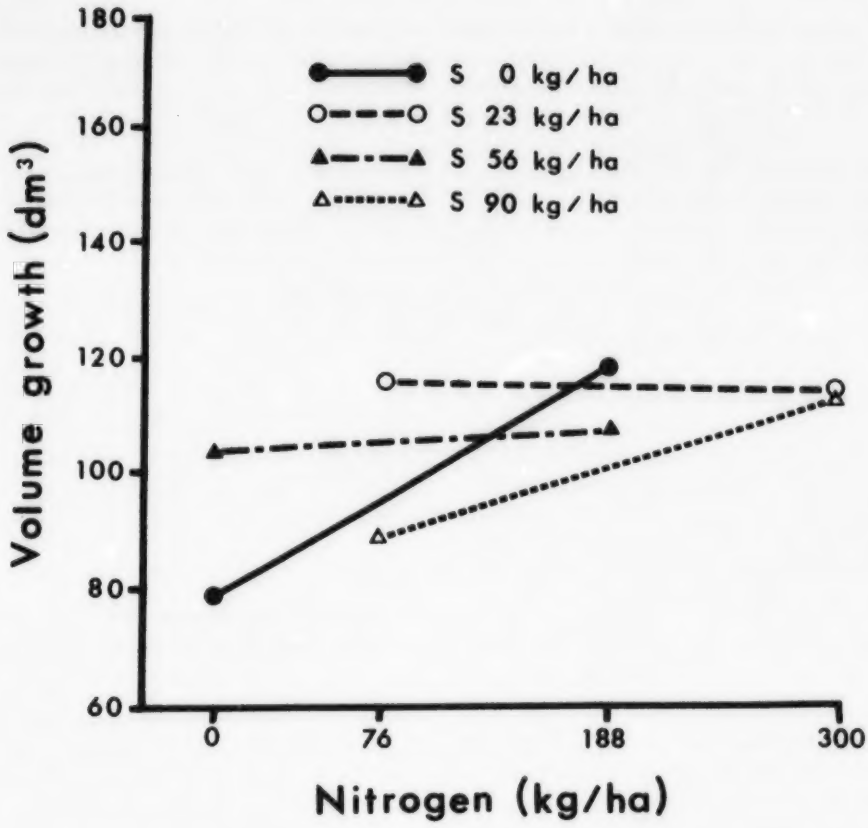

Figure 5. Effects of N × S interactions on 10-year periodic volume increment of dominant-codominant trees on Mercoal soils.

resulted in a significant ($p = 0.05$) response in total stand volume over the control (Treatment 24) on the Coalspur soils and 2 out of 18 on the Mercoal soils.

Response pattern to fertilization was similar in basal area and total and merchantable volumes. Four fertilizer combinations (Treatments 2, 6, 8, and 13) significantly ($p = 0.05$) improved stand basal area and total and merchantable volume increment on the Coalspur site. The best gains amounted to an average of 2.84 m^2 (44%), 34.07 m^3 (44%), and 33.28 m^3 (48%) per hectare for stand basal area, total volume increment, and merchantable volume increment, respectively, over 10 years after adjustment for initial basal area.

The nutrient requirement of lodgepole pine on Mercoal soils differed from that on Coalspur. The best gains in stand increments were found after fertilizer application at rates of 300 kg/ha of N, 150 kg/ha of P, and 90 kg/ha of S (Treatment 8), and 188 kg/ha of N, 94 kg/ha of P, and 113 kg/ha of S (Treatment 14). The gains totaled 3.13 m^2 (56%), 31.47 m^3 (57%), and 28.56 m^3 (50%) per hectare for basal area, total volume increment, and merchantable volume increment, respectively, over the unfertilized plot.

Factorial analyses (not presented here) of basal area and total and merchantable volume increments were conducted to explore the response trends to fertilization. The results showed the effects of N, P, and S on these stand increments were not statistically significant, probably because of the relatively small sample size of the nested factorials. Apparently, in a 2^3 factorial experiment more than three replications of each treatment are required for effective detection of fertilization effects on growth.

Table 7. Mortality rates of 70-year-old stands on the Coalspur and Mercoal sites based on 30 tagged trees

Treatment	Coalspur (%)	Mercoal (%)
1	0	16.7
2	0	0
3	0	10.0
4	0	10.0
5	0	10.0
6	0	6.7
7	0	6.7
8	0	6.7
9	3.3	6.7
10	0	10.0
11	0	10.0
12	0	0
13	0	16.7
14	3.3	6.7
15-20	1.7	9.1
21	6.7	10.0
22	0	6.7
23	0	3.3
24	3.3	0
Average	1.1	7.9

DISCUSSION

Growth responses in this study are generally in agreement with what was indicated by pretreatment foliar nutrient analysis. Although Swan's (1972) provisional standards were based on young seedlings and may not be directly applicable to diagnosing nutritional status of older trees, the standards were quite appropriate to these 70-year-old stands. Pretreatment foliar analysis suggested that there would be a stronger growth response to N than P fertilization, and this diagnosis was borne out by the field trials. Foliar analysis can therefore be used as a diagnostic tool for prescribing tree nutritional requirements. On the other hand, soil analysis results do not lend themselves to easy nutritional interpretations. These results are confounded by lesser vegetation, undergrowth, crop tree density, and rooting habits.

The net gain of up to 50% in stand volumes in response to best N, P, and S fertilizer treatments compares favorably with the response reported by Bella (1978) on fertilization of a thinned lodgepole pine stand. He reported an average absolute increase in gross production of 6.8 m^3/ha (27%) in total volume and 7.5 m^3/ha (31%) in merchantable volume attributable to application of N for a 7-year period. A below-average site and a reduced vigor of trees that were previously growing under fairly dense conditions may explain the lower gain reported by Bella.

Although a net gain in total or merchantable stand volume rather than in individual tree volumes is the chief criterion in evaluation of fertilization effects, gains by individual trees can readily be extrapolated into stand statistics, provided there is no excessive mortality. The four fertilizer treatments that improved tree PVI on the Coalspur soils were the same as those that resulted in the best yield gain on the stand basis (Table 8). The volume gain averaged 43-65 dm^3/tree over the unfertilized trees (Treatment 24) during the 10-year period (Table 5). This would translate into a stand gain of at least 30 m^3 in 10 years following fertilization, assuming 700 dominant and codominant stems per hectare.

Table 8. Ten-year stand increments after different N, P, and S treatments (adjusted for initial basal area)

Treatment	Coalspur			Mercoal		
	Basal area (m^2/ha)	Total volume (m^3/ha)	Merchantable volume (m^3/ha)	Basal area (m^2/ha)	Total volume (m^3/ha)	Merchantable volume (m^3/ha)
1	5.41	58.87	60.71	6.77	70.32	70.65
2	9.03*	95.21*	97.08*	6.61	65.97	68.08
3	6.71	68.74	72.81	7.11	71.71	73.40
4	6.90	75.78	79.20	7.70	78.02	77.99
5	6.33	66.22	69.14	6.62	64.45	65.31
6	8.52*	88.93*	89.43*	6.67	66.57	67.62
7	7.39	78.30	83.78	6.14	61.11	60.86
8	7.97	81.91	84.54	8.70*	86.58*	86.18*
9	6.95	71.39	71.55	6.49	65.30	66.06
10	9.23*	99.09*	102.82**	7.64	76.15	75.57
11	6.42	63.97	66.60	6.48	62.14	61.56
12	7.44	77.78	80.58	6.94	69.44	69.35
13	9.26*	94.65*	93.64*	6.13	63.45	63.21
14	6.68	71.35	77.56	8.41*	85.23*	85.17*
15-20	7.70	80.98	83.68	7.11	70.51	71.81
21	6.71	72.50	73.13	6.52	65.49	66.79
22	6.31	68.17	73.13	6.42	65.13	65.42
23	5.55	58.34	61.35	6.51	64.63	65.01
24	6.39	65.02	69.54	5.57	55.11	57.62

* Treatment means differed from the control at the 5% level.

Growth responses to fertilization on Mercoal soils were less consistent because of high mortality. Fertilization of 377 kg/ha of N, 94 kg/ha of P, and 56 kg/ha of S (Treatment 10) in combination improved PVI by 66 dm^3 per tree or 96% over the unfertilized trees in the 10-year period (Table 5); nevertheless, this treatment showed only a moderate gain in stand PVI because of mortality loss. To sidestep this problem, stand PVI based on the 15 largest trees from tallies of each plots was analyzed. The analysis (Table 9) confirmed that Treatments 6 and 8, which improved tree PVI the most (after Treatment 10 and before adjustment for initial volume), were also the best in terms of stand PVI based on the 15 largest trees per plot. The fertilizer consisting of 300, 38, and 90 kg/ha of N, P, and S, respectively (Treatment 6), in combination consistently improved stand yields on both soil types.

Stand density had a strong modifying effect on growth response to fertilization as reported by other investigators (Shumway and Atkinson 1978). Applications of needed nutrients to more-open stands resulted in a marked increase in PVI, e.g., Treatment 6 (pretreatment volume 250 m^3/ha, PVI 161 dm^3) on the Coalspur soil and Treatment 10 (pretreatment volume 250 m^3/ha, PVI 135 dm^3) on the Mercoal soil. The density-fertilizer interaction might also account for the significant increases in the PVI for Treatment 7 (pretreatment volume 202 m^3/ha) on the Coalspur and Treatment 1 (pretreatment volume 241 m^3/ha) on the Mercoal soil, where only 76 kg/ha of N were added (Table 5). In addition to the somewhat lower nutrient status of the Coalspur soil, lower density may have also contributed to the generally greater growth response to fertilization. Apart from improving tree growth, fertilizing stands with lower density might also reduce mortality.

The influence of stand density on fertilizer response in conifers, particularly response to nitrogen, has been reported by many investigators (Steinbrenner 1968; Woollons and Will 1975; Mead and Gadgil 1978;

Table 9. Stand basal area, total volume, and merchantable volume increments for the 15 largest trees per plot on the Mercoal soils

Treatment	Basal area (m^2/ha)		Total volume (m^3/ha)		Merchantable volume (m^3/ha)	
	Increment	Adjusted	Increment	Adjusted	Increment	Adjusted
1	5.13	5.20	53.77	54.35	52.93	53.45
2	4.93	4.89	50.59	50.26	49.79	49.49
3	5.23	5.44	54.20	55.93	53.44	55.00
4	4.81	5.16	51.30	54.12	50.67	53.20
5	4.59	4.64	45.76	46.15	45.25	45.60
6	6.69	6.57*	66.85	65.90*	65.74	64.89*
7	4.34	4.33	44.81	44.67	44.06	43.94
8	6.34	6.31*	65.61	65.37*	64.37	64.15*
9	4.52	4.63	46.33	47.24	45.67	46.49
10	5.37	5.45	54.40	55.07	53.61	54.22
11	4.66	4.43	46.37	44.45	45.58	43.85
12	4.89	5.17	50.33	52.57	49.87	51.88
13	5.38	5.49	54.73	55.69	53.31	54.17
14	5.95	6.10	62.22	63.47	61.33	62.46
15-20	5.25	5.12	53.49	52.48	52.70	51.80
21	5.55	5.46	57.63	55.89	55.69	55.03
22	3.56	3.42	37.64	36.48	36.96	35.92
23	5.34	5.26	53.34	52.66	52.63	63.03
24	3.84	3.92	39.11	39.73	38.65	39.21

* Adjusted means differed from the control at the 5% level.

Shumway and Atkinson 1978; Timmer and Fisher 1978). More response may result from expanded photosynthetic surface than from improved photosynthetic efficiency (Fagerstrom and Lohm 1977). Consequently, overstocked stands, with no room for crown expansion, seldom show much net growth response to nitrogen fertilization.

Yield gains to any silvicultural treatments are a function of the improved growth rate as well as the level of growing stock. While fertilizing dense stands is nutritionally inefficient, fertilizing understocked stands is not cost-effective. On the Mercoal site, trees of Treatment 6 (300, 34, and 90 kg/ha of N, P, and S, respectively) and Treatment 10 (377, 94 and 56 kg/ha of N, P, and S, respectively) showed marked responses in tree PVI (Figs. 3 and 4), but no significant improvement in stand PVI (Table 8), owing to the relatively lower growing stock on these plots (Table 2). The level of growing stock could therefore be an influencing factor in choosing stands for fertilization treatment. Higher stand response can be ensured by fertilizing stands of optimum density.

CONCLUSIONS

The following summarizes the results and conclusions drawn from this study:

1. N, P, and S fertilization of 70-year-old lodgepole pine stands on two luvisols in west-central Alberta improved average stand productivity as much as 31-34 m^3 in total volume per hectare and 28-33 m^3 in merchantable volume per hectare over a 10-year period. This is almost a 50% improvement in wood production after fertilization, even taking mortality loss into account.

2. Growth responses to fertilization are generally in agreement with the results of pretreatment foliar analysis, indicating the potential value of such analysis as a diagnostic tool for prescribing nutrient requirements.

3. N is the nutrient in greatest demand for lodgepole pine growth on the two luvisols studied. An addition of 188 kg/ha or more of N is needed for significant response on these soils. On Coalspur soils, an application of P in the range of 38-94 kg/ha, in addition to the required N, improved tree PVI.

4. The results are inconclusive about the S requirement of lodgepole pine. Whether the results are in fact peculiar to this study requires further investigation.

5. Response to fertilization is also influenced by stand density; higher tree and stand response may be ensured by fertilizing stands of optimum density.

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